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2. Patent application number *(The Patent Office will fill in this part)*: 16 MAR 2004 — 0405897.0

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   Pyroban Group Limited
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   Dolphin Road, Shoreham-by-Sea
   West Sussex
   BN43 6QG

   Patents ADP number *(if you know it)*: 8308500001

   If the applicant is a corporate body, give the country/state of its incorporation: United Kingdom

4. Title of the invention

   Exhaust Filter Regeneration Regime Method and Apparatus

5. Name of your agent *(if you have one)*

   "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*:
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11. I/We request the grant of a patent on the basis of this application.

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EXHAUST FILTER REGENERATION REGIME METHOD AND APPARATUS

The invention relates to an exhaust filter regeneration regime, method and apparatus for example for use in a diesel engine exhaust stream.

Such equipment is used in the removal of carbon monoxide, hydrocarbons and NOX pollutants and particulates made in exhaust systems.

In known systems, soot removal is usually achieved most effectively through the use of a filter. Regenerated traps, such as CRTs (Continuously Regenerated Traps), work on the principle of retaining soot particles within a ceramic or silicone carbide filter often termed a diesel particulate filter (DPF), which collects the soot particles within porous walls of the honeycomb structure of the filter. The accumulation of this soot within the surface of the filter increases the backpressure of the filter, which then requires the filter to be regenerated.

Regeneration is achieved when the exhaust temperature reaches above around 600°C at which point the component of the exhaust gas stream reacts with the soot creating an exothermic reaction, which increases the trap temperature as soot is oxidised and burnt away. The regeneration occurs at a lower temperature in the presence of a catalyst.

The temperature of the exhaust gas and filter are critical to the regeneration process, which lead to various problems with the technology. For example, for certain engine duty cycles it is not possible to achieve an exhaust gas temperature which enables unassisted regeneration.

It is known to reduce the regeneration temperature by introducing a catalyst component upstream of the filter, which reacts with the upstream exhaust gas to create an NO_2 enriched atmosphere. This stimulates the regeneration burning process enabling regeneration temperatures to be reduced to around 380°C. There are, however, cases where the engine duty cycle is such that exhaust stream temperature never exceeds the 380°C regeneration target temperature and, therefore, other approaches are required to assist with the regeneration.

One known solution to this is set out in "Particulate Trap Technology for Light Duty Vehicles with a New Regeneration Strategy" Zikoridse et al, SAE Technical Papers Series No.2000-01-1924, in which exhaust gas flows through a heating module having a convection section followed by a radiation section before entering a particulate trap to raise the trap temperature. Alternatively, it is known to provide additional heating local to the filter to increase the approach temperature to enable regeneration, or to rely on fuel born catalysts. Auxiliary heating has drawbacks, as it requires more complex links to the vehicle's onboard power system, which in some cases will not be sufficiently sized to cope with the additional load; this also adds expense and maintenance difficulties. Fuel born catalysts, on the other hand, achieve the same result, however, there are growing concerns regarding the further emissions which are produced during this regeneration process.

Yet a further known solution is described in the presentation "Demonstration of the effectiveness of a NOX absorber and particle filter system on a light-duty diesel vehicle" McGill *et al*, Oakridge National Laboratory, presented at Windsor Workshop 2001, Windsor, Ontario. According to that presentation

fuel can be injected into the exhaust stream allowing catalytic reformation.

Further problems can arise with the known systems; the regeneration regime is heavily dependent on temperature and hence on vehicle type and usage, for example vehicle duty cycle. Accordingly, before a soot filtration system can be fitted it is necessary to understand the engine's duty cycle to model the temperature profile of the exhaust gas to gain assurance that it will in fact regenerate the filter. This adds further problems because, for example, in a bus application the bus may have the temperature trending compiled on a motorway route where it is found to reach the correct regeneration temperatures. However, it may subsequently be assigned to an inner city route where exhaust temperatures are not sufficient for regeneration.

The invention is set out in the claims.

As a result the invention allows implementation of the control strategy that is adaptable to multiple usages and duty cycles.

Embodiments of the invention will be described, by way of example, with reference to drawings of which:

Fig. 1 is a schematic block diagram showing an engine implementing an exhaust filter regeneration regime in accordance with the present invention;

Fig. 2 is a flow diagram demonstrating the steps implemented in the regeneration regime control strategy;

Fig. 3 is a flow diagram demonstrating the steps implemented; and

Fig. 4 is a schematic block diagram showing a further improved approach to enhancing the regeneration regime.

In overview, referring to Fig. 1 which shows in block diagram the principal components of an engine incorporating the system according to the invention. It will be seen that air is fed from inlet manifold 10 to an engine 12 from which the exhaust is fed to an exhaust manifold 14. The exhaust stream then passes through exhaust conduit 16a to a catalytic reducer 18 for reducing CO and HC. The reduced exhaust stream then passes via exhaust conduit 16b to a diesel particulate filter (DPF) 20 where particulate matter such as soot is removed from the exhaust stream and the exhaust stream passes through exhaust conduit 16c. A fuel injector 22 is provided in the exhaust manifold 14, near the outlet to benefit from highest exhaust stream temperature. The fuel metered by the fuel injector 22 into the exhaust stream is oxidised by the catalytic converter 18 thus providing heat. The heat assists in raising the temperature of the DPF 20 to an appropriate level to allow combustion in conjunction with the oxygen present and beyond. As discussed in more detail below significant temperature increases up to the required level of approximately 550^{O}C are available by this approach.

The system further includes a regeneration controller which can be separate from or part of an engine control unit ((ECU) 24 which controls the fuel injector 22 and also receives signals from sensors 26, 28, 30, 32, 34, 36, 38 and 40 as described in more detail below. Based on the sensed signals the ECU 24 implements a fuel injection strategy by fuel injector 22 to obtain the desired level of regeneration of DPF 20. In particular the sensed signals are used to

determine when to switch fuel injection on and off and hence commence and terminate regeneration. Fuel Injection start is triggered when the DPF is detected to exceed a predetermined particulate load and the relevant temperature conditions are detected for commencement of the catalytic reaction with the injected fuel in the catalytic converter 18. Similarly, fuel injection is terminated when the particulate load is detected to drop below a predetermined threshold or when the temperature conditions are detected as being insufficient to support regeneration. The particulate load is determined as a function of the pressure drop across the DPF 20 and mass flow through the engine and the temperature is detected at the catalytic converter 18. The ECU 24 also controls the fuel injection regime via fuel injector 22 to ensure that an appropriate regeneration level is attained. In particular fuel injection is controlled as a function of the temperature of the catalytic converter 18 to avoid production of unburnt fuel in the form of white smoke, resulting from excessive injected fuel.

As a result of this approach a method of regeneration is provided which is controlled entirely by on-board components requiring no operator involvement and which can be achieved for any operating vehicle's duty cycle. In particular it is achieved by artificially increasing the system operating temperature to above 550^{O}C to ensure that soot is burnt off by virtue of the high pressure fuel injection regime providing an increased exhaust gas temperature downstream of the catalytic converter 18.

The specific arrangement and strategies are discussed below together with further optimisations.

Referring to Fig. 1 in more detail, the catalytic converter 18 comprises a high platinum load metal catalyst of a cordierite metal or silicon carbide material with mineral wash coat which is found to reduce CO and HC by up to 95%. The DPF 20 is a silicon carbide filter found to reduce mass particulate by 95% and nearly eliminate visible black smoke. The sensors comprise an inlet manifold absolute pressure (IM_{PA}) sensor 26 and an inlet manifold absolute temperature (IM_{TA}) sensor 28 provided on the inlet manifold 10. An engine speed (ES) sensor 30 is provided on the engine 12, or at the inlet manifold to measure cylinder inlet manifold pressure variation, which fluctuate each time the cylinder ports open hence representing engine speed. A temperature sensor 32 is provided for sensing the temperature of exhaust gas (T_{CI}) immediately before the catalytic converter 18. The sensor 36 senses the temperature of gas exiting the catalytic converter 18 (T_{CO}). Sensor 36 senses the pressure at the inlet to the DPF 20 and sensor 38 senses the pressure at the outlet to the DPF 20 allowing the pressure drop (P_{DPF}) across the DPF to be measured. Sensor 40 senses the temperature T_{DO} of gas exiting the DPF 20.

The manner in which the arrangement and particular sensor values are used in implementing the control strategy of the present invention can be further understood with reference to Fig. 2.

In block 200 the ECU monitors whether the particulate load on the DPF 20, F_{load}, exceeds a predetermined threshold. The value of F_{load} can be derived from:

1. $F_{load} = c\ (P_{DPF} * IM_{TA})/(ES * I_{MPA})$

Where c is a constant that can be calibrated during development of the system or derived from a lookup table.

Equation 1 represents the relationship between pressure drop across the filter P_{DPF}, mass flow and the particulate load. P_{DPF} increases as the filter becomes loaded with carbon until it is necessary to perform a regeneration of the filter to remove the carbon. However, as P_{DPF} is also proportional to the mass flow of gas through the filter it is necessary to normalise P_{DPF} against exhaust mass flow.

The exhaust mass flow is determined by the quantity of air taken in on each engine stroke which in turn determined by the temperature of the air at the inlet manifold (IM_{TA}) and its absolute pressure (IM_{PA}) and the engine speed (ES). The amount of air taken in will fall proportionally with increasing IM_{TA} and increase proportionally with increasing IM_{PA} and ES. This is reflected in Equation 1 above. The threshold value which F_{load} must exceed to trigger regeneration may represent full particulate loading of the filter or partial particulate loading of the filter and may either be stored as a constant in the control software or calibrated during development or installation.

In block 202 the ECU 24 further determines whether the catalytic converter 18 is at a suitable temperature for the combustion of fuel injected into the exhaust stream to take place. In particular, as the catalytic converter will only stimulate oxidation of the fuel at a high temperature above approximately 230^{O}C the system checks that both the input and output temperatures T_{CO}, T_{CI} exceed the threshold temperature. If the particulate load and catalytic converter temperature both exceed the respective thresholds then block 204, the ECU

commences the fuel injector regime. The system then monitors for a trigger event which will terminate the regeneration process. In block 206 the system monitors whether F_{load}, as given by Equation 1 above, falls below a lower threshold representing an appropriate reduction in the particulate load. If it has dropped below the threshold then in block 208 fuel injection is terminated. The system further monitors in block 210 for a reduction in temperature of the catalytic converter 18 such that combustion of the injected fuel will no longer take place as a result of which fuel injection will not be triggered. In particular the system can monitor to establish whether T_{CO} and T_{CI} fall below a lower temperature threshold which in this case may be the same the 230°C threshold value for triggering fuel injection in block 202. If so then once again in block 212 then fuel injection is aborted. As a result of abortion of fuel injection the required temperature rise cannot be achieved. It will be noted that once the catalytic converter is at a high temperature following fuel injection it is possible to maintain the required T_{CO} even if T_{CI} drops such that it may be desirable simply to monitor to establish whether T_{CO} drops below the threshold. Alternatively it will be seen that the fuel injection regime can be varied dependent on the temperature difference across the catalytic converter providing an accurate reflection of the temperature regime within the catalytic converter.

Drops in temperature of the catalytic converter can take place for various reasons, for example because of the duty cycle of a vehicle. One specific example would be the decrease in exhaust temperature if the engine load of a vehicle decreased. The temperature T_{CO} can further be monitored to identify when the Catalytic Converter temperature exceeds a damage threshold.

As an alternative approach, regeneration can be terminated if T_{CO} deviates from a T_{CO} setpoint which the system is attempting to achieve by fuel injection (as discussed in more detail below), for example by more than $30^{O}C$ for more than 10 seconds.

In block 214 the system further monitors to establish whether a time-out condition has taken place. Accordingly a timer is instigated upon commencement of the regeneration process at block 204 and if this exceeds a threshold value, for example 5 minutes, then in block 216 fuel injection is once again terminated.

The system further monitors in block 220 to establish whether the temperature T_{DO} of the DPF 20 exceeds a self-sustaining threshold. When regeneration has been triggered a rapid increase in the temperature of the DPF is seen such that a high T_{DO} indicates that regeneration has been initiated and fuel injection can be terminated. As regeneration is a self-sustaining exothermic reaction no further fuel injection is required although it may be desired to introduce a level of fuel injection necessary to sustain regeneration for example at a lower level than that required to initiate regeneration, but sufficient to maintain the exhaust stream temperature at the desired level.

The system further monitors in block 222 to establish whether the temperature T_{DO} of the DPF 20 exceeds a safe working threshold, for example 1000°C. When T_{DO} exceeds the present working threshold fuel injection and/or regeneration is halted and an alarm condition indicated at block 224.

It will be appreciated that the fuel injection regime in block 204 is preferably controlled so as to achieve optimum efficiency and emissions reduction. In particular it is found that if too much fuel is added the fuel passes straight through the catalytic converter 18 without oxidation resulting in white smoke and also having a quenching effect on the catalytic converter, reducing its temperature. For example only a small amount of fuel should be added at the initiation temperature of 230^{O}C but as the temperature increases a high rate of fuel injection can be tolerated. An appropriate control strategy can be further seen with reference to table 1 and Fig. 4.

T_{CO} setpoint (°C)	**T_{CO} setpoint ramp rate (°C/s)**	**Maximum time (s)**
Up to 270	1	40
270 to 300	2	30
300 to 470	3	56
470 to 490	2	10
490 to 550	1	10
		146

Table I

In block 300, upon commencement of the fuel injection regime, the T_{CO} set point is set as the measured value (reaching 230^{O}C). From a look-up table corresponding to Table I, the corresponding ramp rate can derived for that T_{CO} set point as 1°C per second. As a result the fuel injection is controlled to provide an increase in T_{CO} at that rate. This can be done, for example by varying the amount or frequency of fuel injection. Where the injector is switched on for a short period every 20ms, the period for which the injector

remains on can be varied to meet the required amount of fuel into the exhaust. This period can be determined from a further look up table, for example calibrated upon development of the system or can be determined using a feed-back approach such as a PID (proportional/integral/derivative) control algorithm as a result of which the metering of fuel injection will be rapidly tailored to converge the temperature rate with the desired value. The amount of fuel injection may be reduced for situations where the engine speed and load are high, thereby preventing unwanted pass through of fuel which will increase with pass through. As such table 1 may vary in an additional dimension with engine speed and/or load.

The system continues to measure T_{CO} and in block 302 monitors to establish whether the measured T_{CO} has met the next set point (in the first instance $270^{O}C$ from Table I). If so at block 304 the T_{CO} setpoint is set to the next set point value (i.e. $270^{O}C$) and the set point ramp is determined accordingly. In the examples shown, the set point ramp is increased to 2 degrees per second and the fuel injection regime metered accordingly to achieve this. As a result it can be seen that the ramp rate is slow initially but then increases as the catalytic converter temperature increases and more fuel can be oxidised. The system also checks at block 302 to ensure that the period during which fuel injection has been metered according to the ramp rate does not exceed a time-out period which can be individually determined for each set point value, as set out in Table 1 and is set at the expected time taken to reach the next setpoint or slightly longer. If so regeneration is aborted as the desired temperature rate increase cannot be sustained to initiate regeneration.

The process is repeated until T_{CO} reaches its upper temperature level e.g. 550°C at which point regeneration should be triggered. It will be seen that the set point ramps downwards again as T_{CO} approaches the upper limit to ensure that overshoot is avoided and reduce the risk of production of white smoke from unburned fuel. When setpoint T_{CO} reaches 550°C, fuel injection can be aborted, so as not to exceed the setpoint value. This may be appropriate in situations where regeneration is occurring as a self sustaining exothermic reaction. However, situations may arise where regeneration is not self sustaining and as such it will be necessary to inject fuel to sustain the 550°C set point i.e. at a 0°C/s ramp rate. Again, the rate of fuel injection is dictated by both the engine speed and load and the temperature T_{CO}. It will be seen that the time out period for the higher temperature values is significantly reduced again to avoid overinjection of fuel and providing a maximum time for the fuel injection regime of the sum of the maximum permitted times for each individual step increase.

As a result, once initiated fuel is injected such that a rapid temperature rise is achieved across the catalytic converter 18 so as to increase the probability of a successful regeneration. The possibility of slippage of fuels through the catalytic converter, resulting in unwanted fuel omissions presenting as white smoke is avoided by insuring that fuel is not injected at too high a rate and this is achieved by deriving a relationship between rate of temperature increase (and hence fuel injection) and catalytic converter temperature. As discussed above it will be appreciated that additional parameters can be incorporated to determine the ramp rate, for example increasing engine speeds as at high speeds the duration time of the fuel in the catalytic converter is reduced such as the fuel injection rate may need to be decreased. The temperature of the catalytic

converter can also be monitored at more than one point through the length of the converter to allow optimisation of the fuel injection rate.

It is found that high pressure fuel injection , for example, 100 bar gauge is effective as this creates the most effective dispersion and atomisation of the injected fuel in the exhaust manifold and exhaust stream. An injection repetition rate of 50 hertz allows an appropriate degree of control. In general circumstances the oxygen content of the exhaust gas will be sufficient to allow regeneration but of course additional steps can be taken to ensure that sufficient oxygen is present, in the catalyst if necessary.

It will be appreciated that operation of the system can be further improved by maintaining a history of vehicle operation and regeneration regime. This can be used, for example, to improve the control strategy in various ways. For example it may be observed that regeneration is more efficient at higher or lower catalytic converter temperatures such that the relevant trigger points can be adjusted accordingly. Alternatively it may be observed that a higher or lower DPF pressure drop corresponds to completion or initiation of regeneration such that the full injection regime can be amended accordingly. Further still the specific fuel injection rate strategy discussed above with reference to table 1 can be adjusted for example by adjusting the setpoint step values or the desired rates of combustion. Furthermore the system can identify relationships between fuel injection level, catalytic converter temperature, and temperature rise such that the desired ramp rate can be achieved more quickly. Further still, additional information can be derived from a stored history of performance. For example when a vehicle frequently adopts one or more specific duty cycles then the system may recognise from vehicle operational perimeters that one of those

duty cycles is being entered and adjust the control strategy accordingly. For example when a certain duty cycle involves significant increases in exhaust temperature then a less intensive fuel injection regime may be instigated.

More generally it can be seen that the ramp rate varies inversely with the difference between the temperature set point and a temperature mid point immediate the upper and lower set point limits. Accordingly a more complex ramp rate regime can be obtained by, for example, selecting a "mid point" which may not be centred exactly between the upper and lower temperature set point limits and introducing appropriate constants. This can be adjusted from cycle to cycle based on recorded regeneration regime history data. Alternatively, more a complex look up table can be provided which once again can be dynamically adjusted.

Referring to Figure 4 a further improvement is shown to the arrangement where like reference numerals from other figures refers to like parts. In particular it will be seen that the fuel line 400 running to the fuel injector 22 includes a chamber portion 402 wrapped around or passing through a region containing heated water recirculated from the radiator or engine compartment . As a result fuel to the fuel injector 22 is pre-heated using waste heat as a result of which high temperatures are more easily attained. The various elements and components used to be implement the invention will be well known to the skilled reader and do not require detailed discussion here. For example any appropriate pressure, temperature and engine speed sensors can be adopted and any appropriate fuel injector retrofitted to the exhaust manifold. The system can be controlled by a designated or existing engine control unit under software or hardware implementation of the control approach and algorithms as

discussed above. The control algorithm is implemented via a microcontroller and digital logic with appropriate analogue inputs to an A to D converter. In the case the performance history of the vehicle is maintained this can be stored at memory at ECU or elsewhere in any appropriate form.

As a result of the arrangement described above, an effective and flexible exhaust filter regeneration regime control can be implemented irrespective of the vehicle type or duty cycle introduced allowing rapid and efficient regeneration whilst reducing omissions to the a minimum.

It will be appreciated the invention can be applied to any appropriate engine or fuel type and that fuel injection can take place in any appropriate part of the exhaust stream. The approaches as described above can be described to any appropriate temperature dependent exhaust treatment regime or other temperature raising mechanisms which rely on fuel injection. The fuel injection can be metered by adjusting fuel alignment, fuel injection rate or fuel injection pulse duration, fuel injection pressure variation or fuel type variation. In addition control can be implemented using appropriate sensed parameters of operation of the engine and the exhaust stream components and using any appropriate sensors and injectors.

Claims

1 A method of controlling an exhaust filter regeneration regime in which fuel is injected into an exhaust stream to increase exhaust stream temperature in conjunction with a catalytic treatment element, the method comprising the step of metering fuel injection dependent upon the exhaust stream temperature.

2 A method as claimed as claim 1 in which the fuel injection is metered by controlling one of the fuel injection rate, fuel injection pulse duration, amount of fuel injected, fuel injection pressure variation, injected fuel type variation.

3 A method as claimed in claim 1 or claim 2 in which the exhaust stream temperature comprises the temperature of the exhaust stream at the outlet of the catalytic treatment element.

4 A method as claimed in any preceding claim comprising initiating fuel injection into the exhaust stream when the filter load exceeds an initiation value.

5 A method as claimed in any preceding claim in which fuel injection is terminated upon any of: filter load reducing to a predetermined determination threshold, catalytic treatment element temperature reducing below a termination threshold or regeneration regime period exceeding a time threshold.

6 A method as claimed in any preceding claim further comprising recording a regeneration regime history and modifying the regeneration regime based on the recorded history.

7 A method as claimed in any preceding claim further comprising the step of pre-heating with vehicle waste heat fuel to be injected.

8 A method of triggering an exhaust filter regeneration regime comprising obtaining a value of filter load as function of filter pressure and exhaust mass flow and triggering a regeneration regime when the filter load exceeds a predetermined value.

9 A method as claimed in claim 8 comprising the step of initiating fuel injection into the exhaust stream upon triggering the exhaust filter regeneration regime.

10 A method of triggering an exhaust filter regeneration regime in which fuel is injected into an exhaust stream to increase exhaust stream temperature in conjunction with a catalytic treatment element comprising obtaining a value of catalytic treatment element temperature and triggering the regeneration regime when the obtained temperature exceeds a predetermined value.

11 A method as claimed in claim 10 further comprising obtaining a value of the filter load as a function of the filter pressure and exhaust mass flow and triggering the regeneration regime when the filter load exceeds a predetermined value.

12 A method of controlling an exhaust filter regeneration regime comprising implementing an exhaust stream temperature control strategy, monitoring variation in exhaust stream temperature and at least one control parameter, obtaining a collation between variation in exhaust stream temperature and the control parameter and adjusting the temperature control strategy based on the collation obtained.

13 An exhaust filter regeneration apparatus comprising a fuel injector arranged to be fitted in an exhaust stream and a controller for controlling the fuel injector to implement a method as claimed in any preceding claim.

14 A vehicle exhaust apparatus comprising an exhaust conduit, an exhaust filter regeneration apparatus as claimed in claim 13 mounted to the exhaust conduit and a fuel conduit for providing fuel to the fuel injector in which the fuel conduit is pre-heated by engine waste heat..

15 An engine or vehicle including an apparatus as claimed in claim 13 or 14.

16 A computer programme comprising a set of instructions configured to implement the method as claimed in any of claims 1 to 12.

17 A computer arranged to operate under the instructions of the computer programme as claimed in claim 16.

18 An engine control unit configured to implement a method as claimed in any claims 1 to 12.

19 A computer readable medium storing a set of instructions to implement a method as claimed in any of claims 1 to 12.

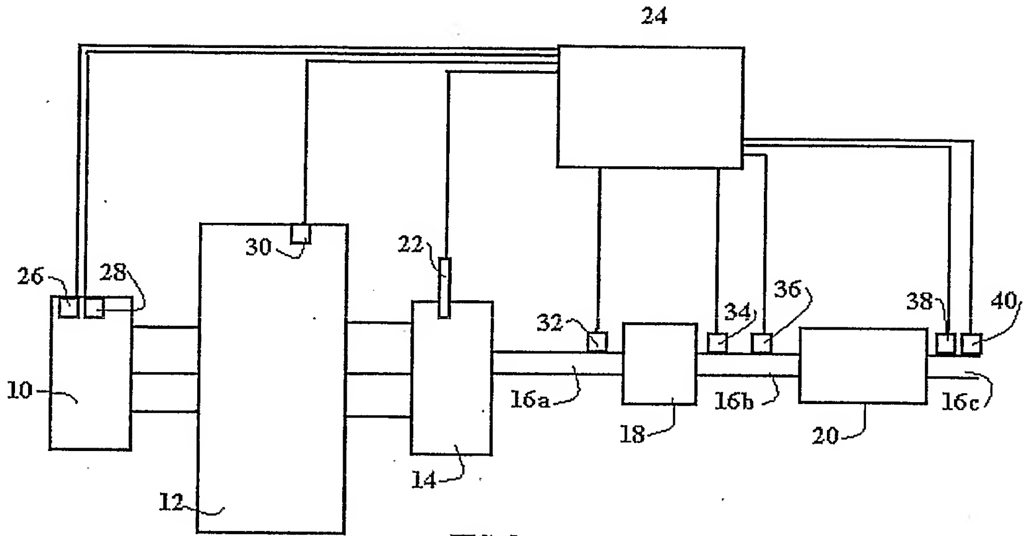

FIG. 1

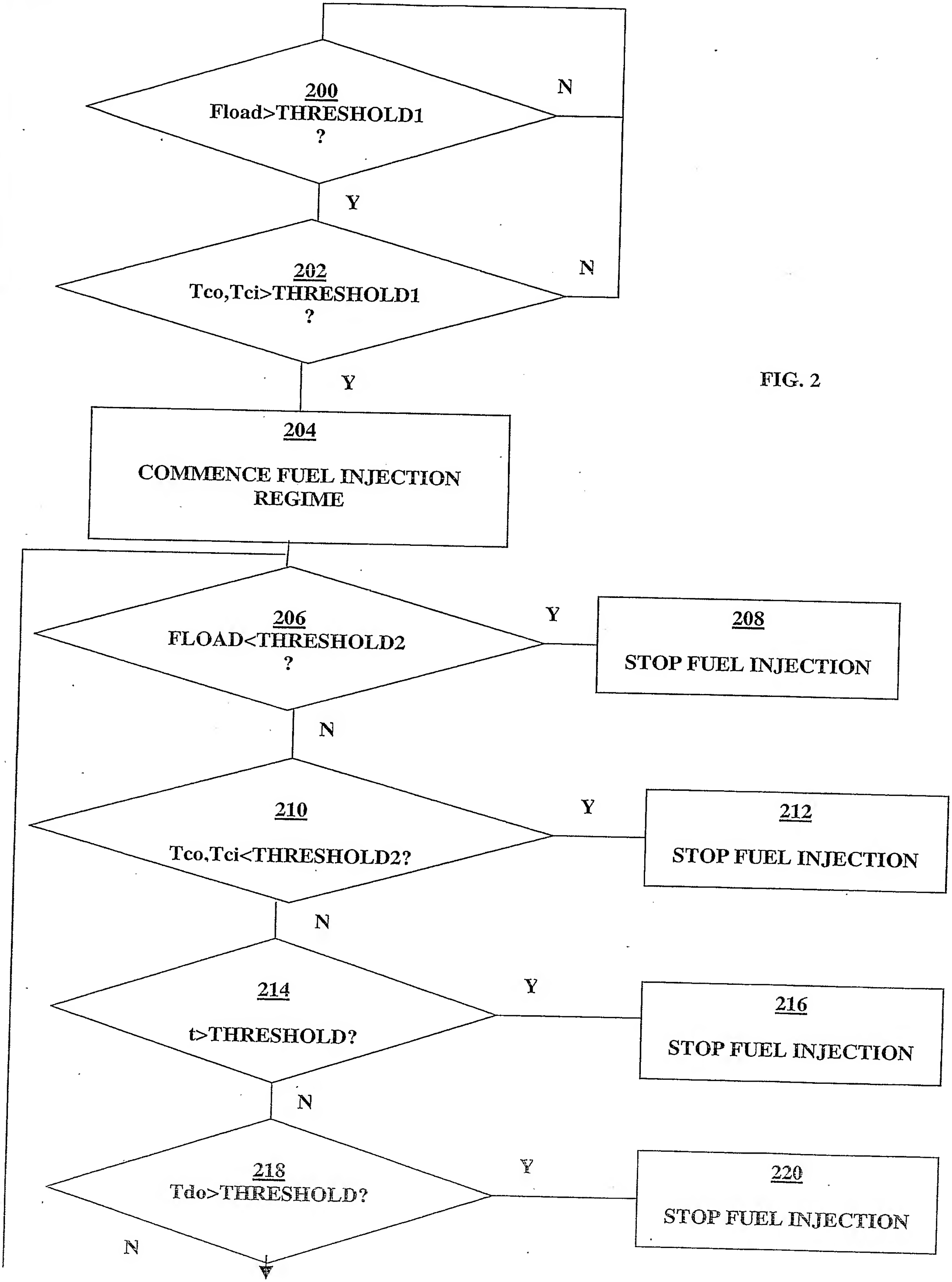
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FIG. 2

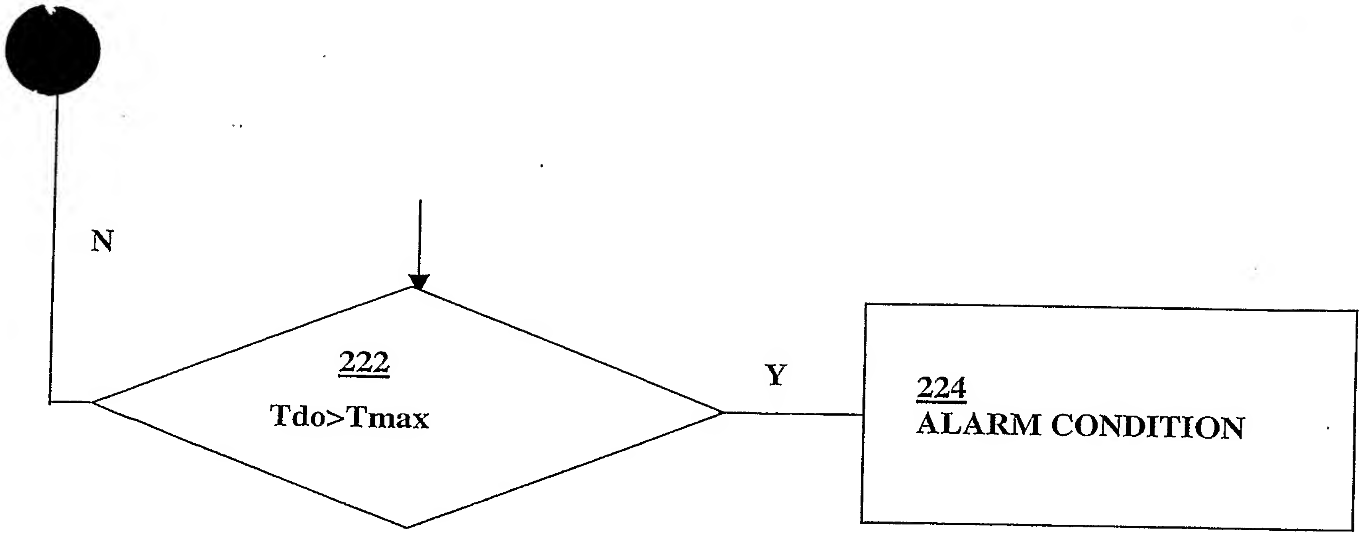

FIG. 2

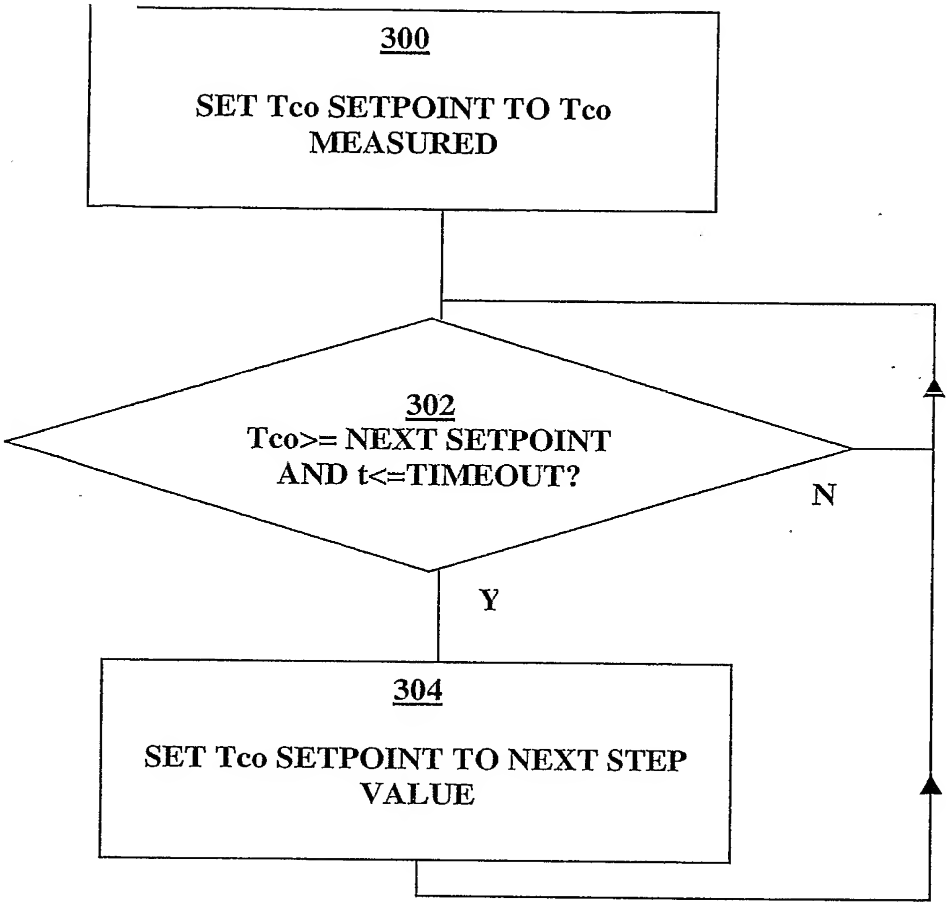
300
SET Tco SETPOINT TO Tco MEASURED
302
Tco>= NEXT SETPOINT AND t<=TIMEOUT?
N
Y
304
SET Tco SETPOINT TO NEXT STEP VALUE

FIG. 3

FIG. 4